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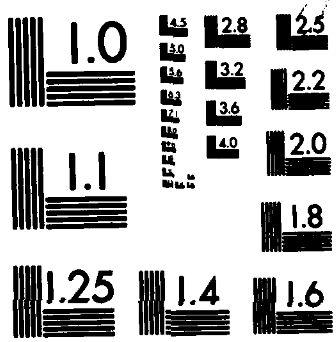

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are reported which were

We present a final report on results obtained during ~~our~~ a theoretical program on the interaction of electromagnetic waves with solids. The report places special emphasis on the 1982 calendar year, which is the final year of the program. We have explored, during the tenure of the program, a variety of interactions which influence the (linear) response of solids to external electromagnetic radiation, with emphasis on the frequency regime which extends from the visible, through the infrared and down to the microwave. Examples are the study of intrinsic free carrier scattering mechanisms in doped, polar materials, where our theory provides an excellent account of data with no adjustable parameters. Also, the scattering of electrons from phonons and other electrons in the near proximity of the surface, and their influence on the microwave response of metals has been explored. The last few years of the program saw increasing emphasis on the propagation of waves along interfaces with nonplanar profile (rough surfaces, periodic grating structures), and on the nonlinear interaction between waves in the near vicinity of planar, and nonplanar interfaces. In this body of work, perturbation theoretic methods were developed, which treat the deviations from a perfectly flat profile as small, and also we had considerable success with nonperturbative methods applied to periodic structures possibly of large amplitude.

1. <u>Research Objectives</u>

The funds from this contract funded a five year effort devoted to theoretical studies of the interaction of electromagnetic radiation in solids; during the course of the program, we made occasional excursions into other areas, where theoretical analyses and their results could provide us with further insight into the principal subject area of the contract. In this section, we present an overview of the research completed during the course of the entire contract. Section 2 is devoted to a discussion of specific projects completed during the 1982 project year; this period has not been discussed in any of the previous annual or semi-annual reports.

The program has had a broad scope, as opposed to one tightly structured around the study of a particular range of frequencies or specific set of processes. Thus, we have studied interactions which influence the electromagnetic response of solid materials from the visible down to the microwave regime. A certain fraction of our effort was devoted to the study of intrinsic (bulk) mechanisms. For example, we have in place a very successful sequence of studies of free carrier relaxation in narrow gap materials (PbSe,PbTe) which now provide a fully quantitative account of the magnitude, frequency, and magnetic field variation of the relaxation rate. Also, these materials can undergo ferroelectric phase transitions, in which the optical phonons soften. Such dramatic changes in material properties, intimately related to their infrared response characteristics, can be probed by light scattering spectroscopy. A theory of these soft modes, their interaction with acoustical phonons and with free carriers, was developed along with a detailed description of the light scattering spectra to be expected.

We also examined other classes of problems which explore bulk mechanisms. Intermediate valence compounds have spin fluctuations of the conduction electrons with characteristic frequencies in the infrared. We first carried out a self consistent field description of the system in the Hartree-Foch approximation using a standard model (Anderson lattice); here the wave vector and frequency dependent spin susceptibility was studied also. Our former postdoctoral researcher Professor P. Riseborough has recently used the information obtained from this study to analyze the infrared optical conductivity of such materials. Also, we developed a theory of the microwave surface impedance of metals, which showed that in the anomalous skin effect regime, electron-electron "N processes" which fail to contribute to the D.C. electrical resistivity, enter prominently.

Another active topic of research was the influence of strong electrons-phonon coupling on localized electronic transitions, most particularly under conditions where one state is degenerate. One then encounters the Jahn-Teller effect; a theoretical description of the influence of the Jahn-Teller effect on the dynamical response of impurity centers was developed. Also,

while the Jahn-Teller effect has been much discussed in the context of electronic transitions in the visible frequency range, in principle it should enter the theoretical description of infrared absorption by localized vibrational modes in crystals. A theory of the influence of the Jahn-Teller effect in this spectral regime was developed.

So throughout the contract period, the study of intrinsic and extrinsic absorption mechanisms in solid materials was an important theme, and new physical mechanisms were elucidated in the course of the program, as the above examples indicate.

As the program evolved, linear and nonlinear optical interactions that occur near surfaces and interfaces occupied an increasingly large fraction of our time and energy. One encounters elementary excitations localized near surfaces or interfaces (surface polaritons, surface acoustic waves, surface spin waves, ...), and under suitable conditions incident electromagnetic radiation may couple to these entities. One may thus study their basic properties, for example, by a technique such as light scattering spectroscopy, and the waves serve as a diagnostic tool affected by changes in the surface or interface geometry. Also, coupling of electromagnetic waves to surface polaritons can enhance electric or magnetic fields near an interface, thus rendering the spectroscopy of this region viable by enhancing the signal.

In our view, the total body of research completed during this phase of the program constitutes a major contribution to a rapidly growing field. We have studied nonlinear phenomena (light scattering, second harmonic generation, etc.) which involve, in effect, mixing of an external electromagnetic wave with a surface excitation. A portion of this theoretical effort has been brought into contact with data in an impressive quantitative fashion, and in fact our theories have served to guide the field, in that we have been lead to new predictions subsequently found in the experiments.

Another phase of the program involved the study of basic properties of surface excitations, most particularly their behavior on surfaces or interfaces that are not smooth. Two limiting cases are the randomly rough surface, and a perfectly periodic diffraction grating. The interactions of surface polaritons with such perturbations has been studied, the coupling of external radiation to surface polaritons via such deviations in the surface profile have been examined, and the theory has also been extended to Rayleigh surface acoustic waves, where again quantitative contact with data has been established. The theoretical investigations have, in some of the work, developed methods which treat deviations from flatness by perturbation theory, and other studies explore large amplitude surface features by nonperturbative theoretic approaches.

Earlier annual and semiannual reports cite and discuss specific papers in this area, and section 2 of the present report also covers research completed in the final 1982 contract year. Thus, in the present section, we shall not discuss specific pieces of research, but we confine our attention to the general area.

We conclude this section with some comments on the spirit and philosophy which has formed the basis for the program. While the title of the contract refers only to the electromagnetic response of solids, we have clearly explored other conceptually related areas. An example are the papers on propagation of surface acoustic waves. We feel strongly that any research effort aimed at fundamental issues must be given the flexibility to explore areas related to the main line of research, if it is to be truly effective in the long term sense. A large fraction of present day research in the U.S. is tightly constrained to follow a pre-conceived and narrow path; when this is done the result is frequently mundane and uninspired research results, with little room for creativity. Most exciting new results are not the result of planning two or three years in advance of attack of the problem. So as we managed our effort, we have allowed ourselves and other researchers associated with it to explore other areas where the techniques we have developed may prove useful. A large volume of research has been completed on the main topic area, and our view is that some of these "offshoots" will provide a major stimulus to other subfields important in future years.

An important issue in the planning of research projects is the time scale. Our frank impression is that the time scale employed by AFOSR is a very short one; that is to say the basic research funded by the agency is work that will have an impact on Air Force problems on a short time scale. One is then confined to funding research that is simply a straightforward extrapolation of presently available results and procedures, with the consequence that the work will indeed have an impact on a short time scale. But one is unlikely to fund research which truly points out new paths to follow with this approach; the decision making process rules out new innovations that are not perceived well in advance.

The two principal investigators have been funded by AFOSR for many years, including more than a decade before the present contract began. During the early years, we were forbidden to pursue certain areas of research initiated by us, since these were not perceived to be of immediate interest to AFOSR. We note that in some cases, AFOSR presently funds research in precisely these areas; our AFOSR supported research led to papers which are now regarded as fundamental early work. On a time scale of one or two years, it was indeed difficult to perceive how the research would directly contribute to Air Force interests. On a longer time scale, the order of a decade, one sees that there is indeed direct impact of the work on Air Force related problems;

none of us (principal investigators included) could see ahead far enough to appreciate why this would be so. During recent years, we have experienced similar pressures, and already we can begin to see how our research couples to Air Force interests. We have thus managed our present effort in a fashion that allows for intellectual flexibility, and we hold the very strong view that such an approach is in the best interests of the Air Force, over the long term.

2. (a) Research Completed During the 1982 Contract Year

We now discuss specific research projects completed during the final contract year, the 1982 calendar year.

Quite recently, there has been considerable interest in the response of the surface of magnetic media to external electronmagnetic waves, and in the basic properties of surface spin waves or surface polaritons on such surfaces. We have developed the theory of spin waves in multilayer structures where, say, one has a stack of layers constructed from a ferromagnetic film of thickness d_1, and a nonmagnetic film of thickness d_2. We developed the theory of spin waves in a semi-infinite stack of such films, and also the theory of light scattering from the normal modes of such a structure. We made the novel prediction that when $d_1 > d_2$, the structure admits a surface mode with frequency above the bands of bulk spin waves, while this mode is absent when $d_1 < d_2$. The prediction has now been confirmed by experiments carried out at Argonne National.

While light scattering spectroscopy has proved a powerful and useful probe of the surface response of many materials, including magnetic materials, the wavelength of light is very long, so microscopic aspects of the response do not manifest themselves in the spectra. It has been argued in the literature that glancing incidence neutron beams may be used for exploring microscopic aspects of surface dynamics (phonons and spin waves), since for a very large number of materials, the neutron wave function decays exponentially as one moves into the crystal. To see if this form of spectroscopy is viable, we have developed a theoretical description of inelastic neutron scattering in such a geometry, and carried through an explicit calculation of the contribution to the cross section from scattering off surface and bulk spin waves. While we indeed obtain a contribution from scattering off short wavelength surface waves, in fact the cross section is on the bare threshold of what can be measured, and the surface mode peak lies very near a stronger feature produced by scattering off bulk spin waves. Our analysis thus ends on a pessimistic note.

As one of us discussed some years ago, antiferromagnets are a particularly suitable magnetic medium within which bulk polaritons may propagate, in the infrared. The waves interact strongly with the spins. In FeF_2, these magnetic polariotns have been observed recently, with properties as predicted. A new

study shows that on the surface of such a material, surface polaritons may also propagate. We have developed the theory of these waves, with quantitative calculations carried through for FeF_2. The surface modes have a highly nonreciprocal dispersion relation, at infrared frequencies, and their dispersion relation is easily "tuned" or varied through a static, external magnetic field.

It is well known that a pulse of bulk phonons may, by virtue of suitable anisotropy in the dispersion relation, will focus down and reduce its angular spread. This important phenomena, possible also for electromagnetic waves in suitble media, has been exploited in a variety of situations. During the 1982 year, we completed a theory of the focusing of a beam of surface phonons. The theory is fully quantitative, and calculations were carried through for (100) and (111) surfaces of Cu, Ge and NaCl. We believe the results will be of value to a number of researchers with interest in surface wave devices.

We have also formulated a nonperturbative description of the interaction of Rayleigh surface acoustic waves with periodic gratings. The dispersion relation for the waves has been studied in detail, with emphasis on grating-induced "radiative damping" of the Rayleigh wave. As the surface mode propagates along the surface, the grating couples it to bulk transverse and longitudinal phonons, with the consequence tht the Rayleigh wave mean free path becomes finite. The calculations reveal the presence of a surface resonance mode to which the Rayleigh wave is coupled, when a grating is on the surface. This resonance shows up as a peak in the attenuation constant of the Rayleigh wave, and a peak very similar to that we calculate appears in experimental data.

As remarked earlier, the theory of light scattering from excitations localized near a surface has been a major thrust of research in the present project, culminating in our sequence of studies of light scattering by spin waves near surfaces. We have also constructed a theory of nonlinear mixing between spin waves localized near a surface, or between bulk spin waves and surface modes. We have here an interesting nonlinear phenomenon of potential interest to microwave devices.

Another major area of research explored during the 1982 contract year is the electromagnetic response of a surface upon which a doubly periodic structure has been imposed. An example of such a structure would be a two dimensional lattice of hemispherical bumps. The virtue of such a structure in practice, compared to the usual diffraction grating, is that one may couple to surface plasmons over a wide range of frequency and angle. We have set up a theoretical description of the interaction of electromagnetic radiation with such a structure, within a nonperturbative framework similar to that used in our earlier work on the grating problems. With this formalism, we have explored the dispersion relation of surface plasmons as they propagate across the structure, and also the reflectivity. The analysis

has been carried through in a regime where perturbation theory proves inadequate.

The discussion in this subsection explores some of the principal lines of research pursued and completed during the 1982 final contract year. Section 2(b) lists the papers that have either appeared in journals during this period, or that have been submitted for publication then. Not all of the research has been discussed here, since our attention has been confined to a few principal lines of work, in this subsection.

2(b): Cumulative Chronological List of Written Publications in Technical Journals; The 1982 Contract Year

During the period covered by this report, the following manuscripts have either appeared in scientific journals, or have been submitted:

1. "Magnetic Excitations in Layered Media: Spin Waves and the Light Scattering Spectrum", R. E. Camley, Talat S. Rahman, and D. L. Mills, Phys. Rev. B27, 261 (1983).

2. "Inelastic Scattering of Neutrons by Surface Spin Waves on Ferromagnets", P. Mazur and D. L. Mills, Phys. Rev. B26, 5175 (1982).

3. "Surface Polaritons on Uniaxial Antiferromagnets" R. E. Camley and D. L. Mills, Phys. Rev. B26, 1280 (1982).

4. "Phonon Focusing at Surfaces", R. E. Camley and A. A. Maradudin, Phys. Rev. B27, 1959 (1983).

5. "Leaky Surface-Elastic Waves on Both Flat and Strongly Corrugated Surfaces for Isotropic, Non-Dissipative Media", N. E. Glass and A. A. Maradudin, J. Appl. Phys. 54, 796 (1983).

6. "Nonlinear Mixing of Bulk and Surface Magnetostatic Spin Waves", R. E. Camley and A. A. Maradudin, Phys. Rev. Letters 49, 168 (1982).

7. "Surface Plasmons on a Large Amplitude Doubly Periodically Corrugated Surface", N. E. Glass, A. A. Maradudin and V. Celli, Phys. Rev. B26, 5357 (1982).

8. "Diffraction of Light by a Bigrating: Surface Polariton Resonances and Electric Field Enhancements", N. E. Glass, A. A. Maradudin and V. Celli, Phys. Rev. B27, 5150 (1983).

9. "Surface Plasmons on a Large Amplitude Doubly Periodic Corrugated Surface", N. E. Glass, A. A. Maradudin and V. Celli, to be published.

10. "Transverse Elastic Waves in Periodically Layered Infinite, Semi-Infinite, and Slab Media" R. E. Camley, B. Djafari-Rouhani, L. Dobrzynski, and A. A. Maradudin, to be published.

11. "Phonons in Confined Geometries", A. A. Maradudin (to be published).

12. "Nonlinear Surface Electromagnetic Waves", A. A. Maradudin (to be published.)

2(c): Professional Personnel Associated with the Contract During the 1982 Contract Year

Professor A. A. Maradudin
Professor D. L. Mills
Professor V. Celli
Dr. N. E. Glass
Dr. P. Mazur
Dr. R. E. Camley
Dr. L. Dobrzynski

2(d): Interactions, 1982 Contract Year

(i) One of the principal investigators (D.L.M.) spent a two week period at the IBM Research Laboratories in Yorktown Heights, N.Y., to discuss implications of AFOSR supported research on light emitting junctions.

ii) One of us (DLM) served as a member of the Army Research Office Study Group on Surface Polaritons, which met at Duke University during March 1982.

iii) D. L. M. was an invited participant in the DARPA meeting "Nonlinear Optical Materials for Laser Protection", La Jolla 1982.

(iv) D. L. M. serves as a member of the Advisory Committee of the Conference on Magnetism and Magnetic Materials, 1982-1985.

(v) D. L. M. is member of the Army Basic Research Committee, National Academy of Sciences

(vi) A. A. M. gave an invited talk on "Phonons in Confined Geometries," at a workshop on submicron structures held at the University of Illinois in June-July, 1982.

(vii) A. A. M. gave an invited talk on "Some New Results for Surface Phonons" at the European Symposium on Lattice Dynamics held in San Miniato, Italy, September, 1982.

(viii) A. A. M. Gave an invited talk on "Transverse Elastic Waves in Periodically Layered Infinite, Semi-Infinite, and Slab Media" at the International Conference on Modulated and Metastable Semiconductors held in Pasadena, California, in December, 1982.